Polarization Observables in Wide-Angle Compton Scattering at large s, $-t$ and $-u$

PR12-17-008

An NPS collaboration proposal to PAC45

David Hamilton for the WACS collaboration

and the Neutral Particle Spectrometer Collaboration
https://wiki.jlab.org/cuawiki/index.php/Collaboration

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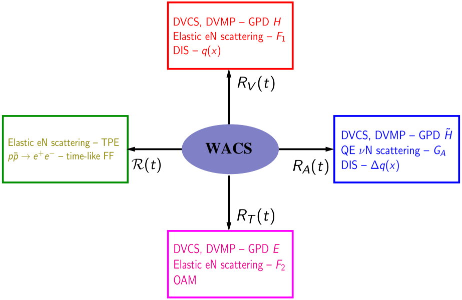
Presentation Outline

- Theoretical context and motivation
  - Factorization of the reaction mechanism
  - Non-perturbative transverse structure of the proton
    - GPD-based approach
    - Soft Collinear Effective Theory
    - Relativistic Constituent Quark Model
- The Jefferson Lab WACS program
  - 6 GeV results and perspectives for the 12 GeV era
- Experimental technique
  - A promising new approach for polarized physics with real photons
- Proposed measurements
  - Initial-state helicity observables at large s, $-t$ and $-u$
- Expected results and beam-time request

WACS: An Introduction

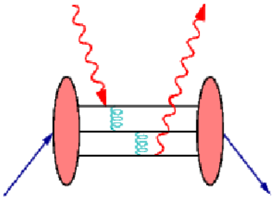
- Hard exclusive nucleon Compton scattering can be investigated in two complementary kinematic regimes:
  - Deeply-virtual: large Q^2; $\left(\frac{-t}{Q^2}\right) \ll 1$
  - Wide-angle: large $-t$, $-u$; $\left(\frac{Q^2}{-t}\right) \ll 1$
- WACS is a powerful yet under-utilised probe of transverse nucleon structure, similar to high-Q^2 elastic electron scattering.
- However, unlike elastic eN experiments WACS is sensitive to the nucleon's axial structure and therefore related to high-Q^2 neutrino scattering experiments.

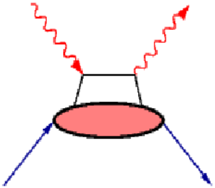


It is one of the least explored of the fundamental reactions in the several GeV regime.

Factorization and the WACS Reaction Mechanism

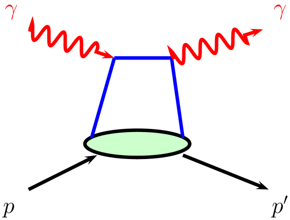
- A number of theoretical approaches have been proposed over the years:
  - pQCD (two hard gluon exchange)
  - Regge exchange and VMD models
  - GPD-based soft overlap mechanism
  - Soft collinear effective theory (SCET)
  - Relativistic constituent quark model
  - Dyson-Schwinger equations
- How does the reaction mechanism factorize?
- Having established the dominant factorization scheme, what new insights on the non-perturbative structure of the proton are accessible?





Non-perturbative Proton Structure: GPD-based Approach

Radyushkin, Phys Rev D58 (1998)
Huang *et al.* EPJ C23 (2002)
Diehl & Kroll, EPJ C73 (2013)



- Provided that $s, -t, -u \gg \Lambda^2$ the handbag mechanism involves factorization of the scattering amplitude into:
  - Hard photon-parton scattering
  - Soft emission and re-absorption of parton by proton

$$\mathcal{M}_{\mu'+,\mu+} = 2\pi\alpha_{\rm em}\left\{\mathcal{H}_{\mu'+,\mu+}[R_V + R_A] + \mathcal{H}_{\mu'-,\mu-}[R_V - R_A]\right\}$$

$$\mathcal{M}_{\mu'-,\mu+} = 2\pi\alpha_{\rm em}\frac{\sqrt{-t}}{m}\left\{\mathcal{H}_{\mu'+,\mu+} + \mathcal{H}_{\mu'-,\mu-}\right\}R_T$$

Non-perturbative physics encoded in vector, axial-vector and tensor form factors which can be related to $1/x$ moments of high momentum transfer, zero skewedness GPDs $H, \tilde{H}$ and E.

Non-perturbative Proton Structure: WACS Form Factors

$\gamma p \to \gamma' p$

$$R_V(t) = \sum_q e_q^2 \int_0^1 \frac{\mathrm{d}x}{x} H_v^q(x,0,t)$$

poorly constrained even at moderate $-t$

$$R_A(t) = \sum_q e_q^2 \int_0^1 \frac{\mathrm{d}x}{x} \tilde{H}_v^q(x,0,t)$$

$$R_T(t) = \sum_q e_q^2 \int_0^1 \frac{\mathrm{d}x}{x} E_v^q(x,0,t)$$

$ep \to e'p$

$$F_1(t) = \sum_q e_q \int_0^1 \mathrm{d}x\, H_v^q(x,0,t)$$

poorly constrained even at moderate $-t$

$$G_A(t) = \sum_q e_q \int_0^1 \mathrm{d}x\, \tilde{H}_v^q(x,0,t)$$

$$F_2(t) = \sum_q e_q \int_0^1 \mathrm{d}x\, E_v^q(x,0,t)$$

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_{\mathrm{KN}} \left\{ \frac{1}{2}\frac{(s-u)^2}{s^2+u^2}\left[R_V^2(t) + \frac{-t}{4m^2}R_T^2(t)\right] + \frac{1}{2}\frac{t^2}{s^2+u^2}R_A^2(t) \right\}$$

$$A_{LL} = K_{LL} = \frac{R_A(t)}{R_V(t)} A_{LL}^{\mathrm{KN}}$$

$$A_{LS} = -K_{LS} = A_{LL}\left[\frac{\sqrt{-t}}{2m}\frac{R_T(t)}{R_V(t)} - \beta\right]$$

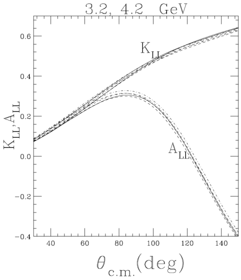
Diehl & Kroll, EPJ C73 (2013)

Kivel & Vanderhaeghen JHEP 4 (2013)

$$\frac{d\sigma}{dt} \simeq \frac{2\pi\alpha^2}{(s-m^2)^2}\left(\frac{1}{1-t/s}+1-t/s\right)|\mathcal{R}|^2 = \frac{d\sigma^{KN}}{dt}|\mathcal{R}|^2,$$

- The Soft Collinear Effective Theory represents an alternative factorized QCD-based approach to WACS.
- It has shown the importance of WACS in understanding two-photon exchange effects in elastic ep scattering.
- In this framework, a new universal form factor is introduced which describes the soft-overlap contribution in a variety of hard exclusive reactions, such as time-like Compton scattering.

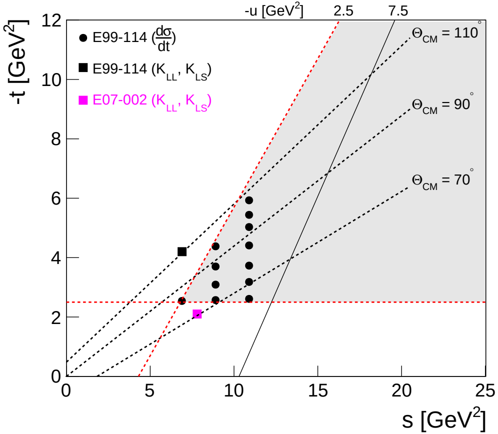
Miller, Phys Rev C 69 (2004)



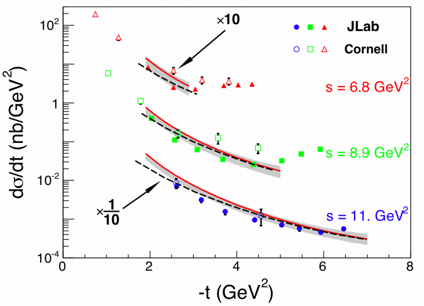
- The relativistic Constituent Quark Model is a handbag-based approach in which relativistic and quark mass effects induce significant quark transverse and orbital angular momentum.
- If the active quark mass is large ($M_p/3$) $A_{LL} \neq K_{LL}$.

The JLab WACS Program – 6 GeV

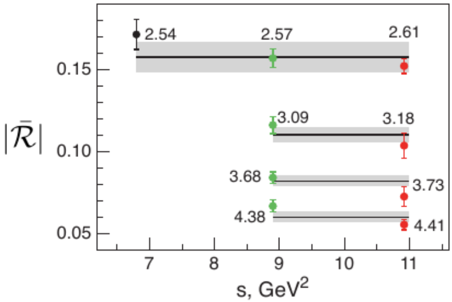
- Two experiments during the 6 GeV era:
  - E99-114 in Hall A with HRS and RCS calorimeter (Pb-glass)
  - E07-002 in Hall C with HMS and BigCal (Pb-glass)



Danagoulian *et al.* PRL98 (2007)



Kivel & Vanderhaeghen JHEP 4 (2013)

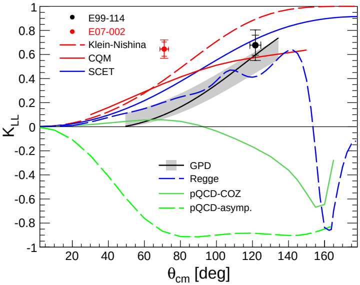


- A factor of 1000 improvement in figure-of-merit over previous experiments.
- Disagreement with pQCD predictions – cross section scales as $1/s^{7.5}$.

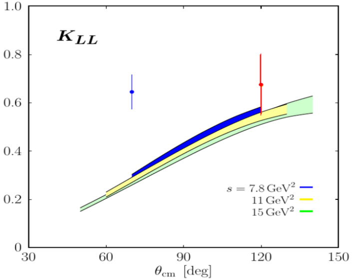
Extracted vector/SCET form factor exhibits strong evidence of s-independence and therefore factorization provided that $s, -t, -u > 2.5\ \mathrm{GeV}^2$.

6 GeV Results – Polarization Observables

Hamilton *et al.* PRL94 (2005)
Fanelli *et al.* PRL115 (2015)



Diehl & Kroll Eur. Phys. J. C73 (2013)



- Results strongly favour leading quark (Feynman) mechanism ($x \approx 1$).
- E07-002 result is larger than all predictions including Klein-Nishina: $K_{LL} = R_A(t)/R_V(t)\, K_{LL}^{\mathrm{KN}} \implies$ large $R_A(t)$.

Hamilton *et al.* PRL94 (2005)
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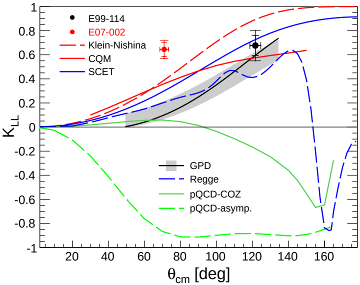
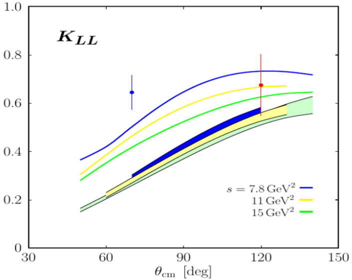


Diehl & Kroll Eur. Phys. J. C73 (2013)
Kroll arXiv:hep-ph/1703.05000 (2017)



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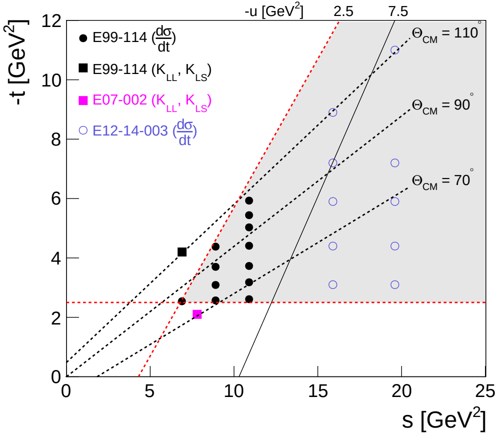
  $K_{LL} = R_A(t)/R_V(t)\, K_{LL}^{\mathrm{KN}} \implies$ large $R_A(t)$.

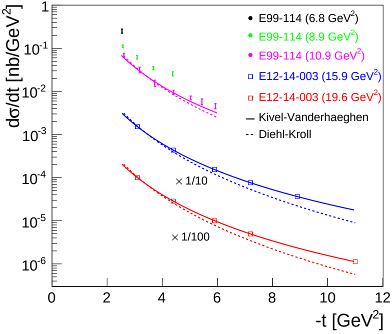
New result suggests axial nucleon current is larger that vector current at moderate $-t$, but validity of factorization and mass corrections are potentially problematic.

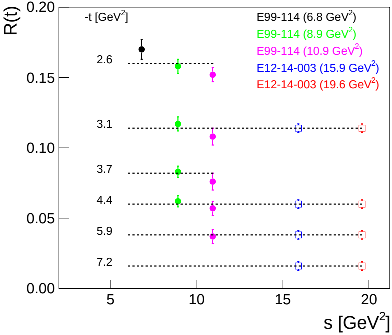
- Two experiments during the 6 GeV era:
  - E99-114 in Hall A with HRS and RCS calorimeter (Pb-glass)
  - E07-002 in Hall C with HMS and BigCal (Pb-glass)
- Cross section experiment approved by PAC42 (A-) for running at 12 GeV:
  - E12-14-003 in Hall C with HMS and NPS ($PbWO_4$)



E12-14-003 – Differential Cross Section

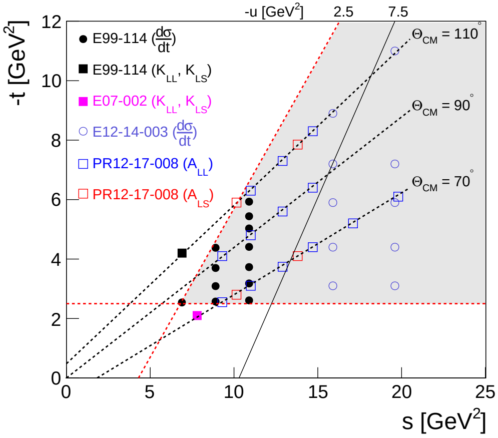
Wojtsekhowski *et al.* JLab Proposal PR12-14-003





- New measurements (all firmly in the wide-angle regime) will allow for a rigorous test of factorization in hard exclusive reactions and extraction of vector/SCET form factor.
- Extension to highest possible values of $-t$ will:
  - Offer new insights into the interplay between hard and soft physics and non-perturbative proton structure.
  - Allow for a direct comparison between $R_V(t)$ and the Dirac form factor (different quark charge and x weightings) and test the universality of leading quark mechanism.

- Two experiments during the 6 GeV era:
  - E99-114 in Hall A with HRS and RCS calorimeter (Pb-glass).
  - E07-002 in Hall C with HMS and BigCal (Pb-glass).
- Cross section experiment approved by PAC42 (A-) for running at 12 GeV:
  - E12-14-003 in Hall C with HMS and NPS ($PbWO_4$).
- This proposal (PR12-17-008):
  - Measurement of A_{LL} and A_{LS} in Hall C with BigBite and NPS ($PbWO_4$).



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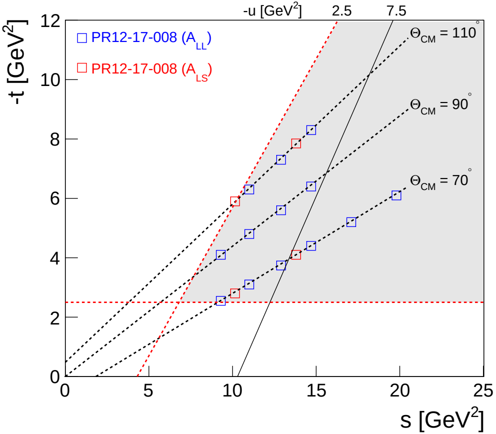
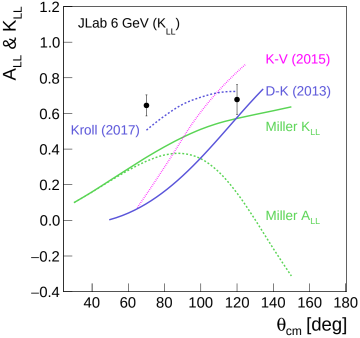
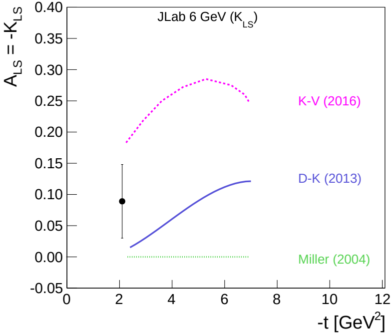
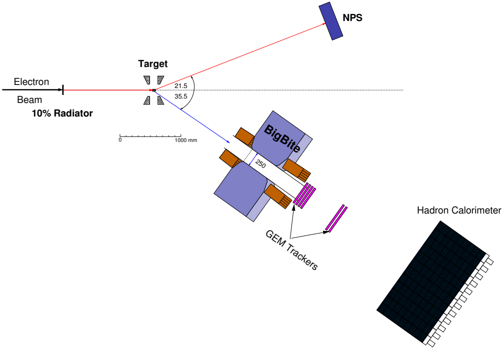






- To what degree is the factorized mechanism dominant and how significant are theoretical corrections?
- What are the constraints on GPD moments and what do they tell us about the proton's axial and tensor structure?
- Is the quark which absorbs and emits photons a constituent or a current quark?
- What does comparison of the SCET and GPD predictions tell us about proton structure and the role of hadron helicity-flip?

1. A 3 μA polarized electron beam incident on a 10 % radiator inside a Compact Photon Source (CPS) produces a high-intensity untagged photon beam.
2. The proton target is the UVA/JLab solid polarized ammonia target.
3. The recoil proton is detected with the BigBite spectrometer equipped with GEM trackers and trigger detectors.
4. The highly-segmented $PbWO_4$ NPS calorimeter is used to detect the scattered photon.



The use of the CPS and BigBite results in a significantly improved figure-of-merit over all previous experiments and opens up a new range of polarized physics opportunities at JLab.

Experimental Technique – Longitudinal Target Polarization

1. A 3 μA polarized electron beam incident on a 10 % radiator inside a Compact Photon Source (CPS) produces a high-intensity untagged photon beam.
2. The proton target is the UVA/JLab solid polarized ammonia target.
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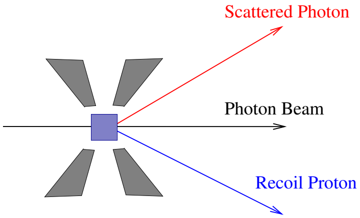
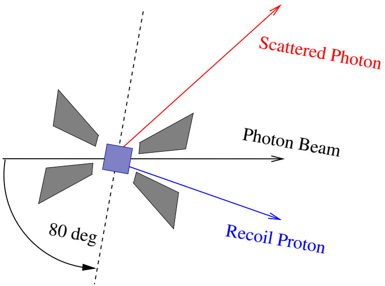


Parallel opening angle between coils is $\pm 50^\circ$.

Experimental Technique – Transverse Target Polarization

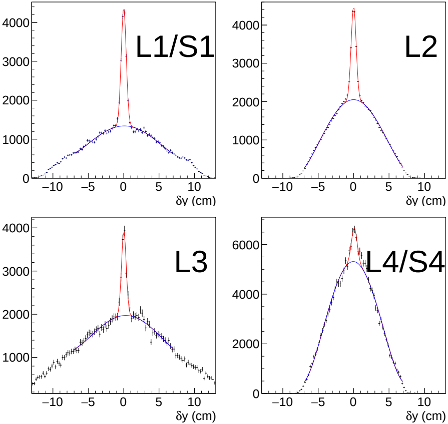
1. A 3 μA polarized electron beam incident on a 10 % radiator inside a Compact Photon Source (CPS) produces a high-intensity untagged photon beam.
2. The proton target is the UVA/JLab solid polarized ammonia target.
3. The recoil proton is detected with the BigBite spectrometer equipped with GEM trackers and trigger detectors.
4. The highly-segmented $\mathrm{PbWO_4}$ NPS calorimeter is used to detect the scattered photon.



Perpendicular opening angle between coils is $\pm 18^\circ$.

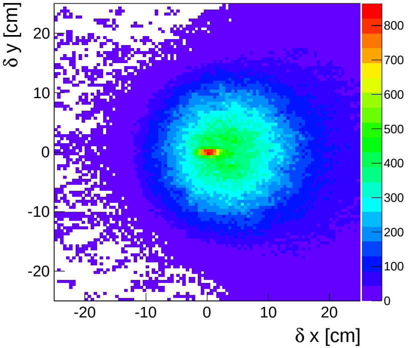
Analysis Technique

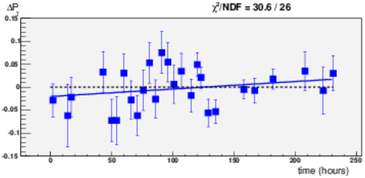
- Data analysis relies on utilization of the kinematic two-body correlation between the scattered photon/electron and the recoil proton.
- The three dominant reaction channels within acceptance are:
  - $\gamma p \to \gamma p$
  - $\gamma p \to \pi^0 p$
  - ~~$ep \to ep$ and $(ep\gamma)$~~
- Robust extraction of the WACS signal requires:
  - Excellent angular and momentum resolution in both the photon and proton spectrometers.
  - Precise determination of π^0 background shape, particularly at large scattering angles.



The use of a pure photon beam and large acceptance spectrometers makes the data analysis significantly simpler and reduces overall systematic uncertainty.

- As in previous JLab WACS experiments, observables for π^0 photoproduction will also be extracted.
- The expected π^0 yield is a factor 50 - 300 times larger than the WACS yield.
- The polarization observables for this channel will therefore be measured to very high statistical precision: so much so that they will be used as an online relative monitor of target polarization.
- A_{LL} is expected to be highly sensitive to twist-3 contributions, which are likely the source of the large discrepancy between data and GPD-based predictions for the cross section (Peter Kroll).





Proposed Measurements – Choice of Kinematic Settings

θ_p^{cm}	E_{Beam}	A_{LL}	A_{LS}
70°	8.8 GeV	✓(50 hours)	✓(100 hours)
70°	11.0 GeV	✓(50 hours)	×
90°	8.8 GeV	✓(150 hours)	×
90°	11.0 GeV	×	×
110°	8.8 GeV	✓(300 hours)	✓(300 hours)
110°	11.0 GeV	×	×

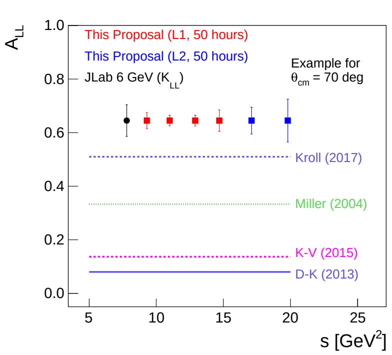
× – low rate or low $-u$

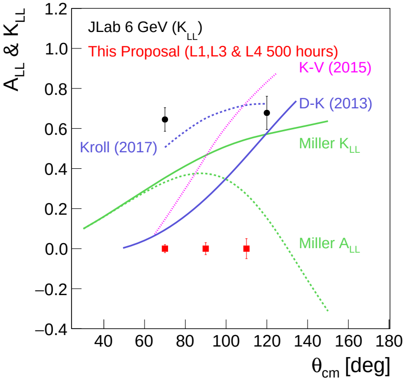
- The development of a new experimental technique based on the CPS and large solid-angle spectrometers makes it possible at last to exploit fully the kinematic range accessible as a result of the 12 GeV upgrade.
- The choice of kinematic settings was driven by:
  - The data **in all bins for all settings** meet the wide-angle condition (s,$-t$,$-u > 2.5\ \mathrm{GeV}^2$).
  - Push to as high as possible in s, $-t$ and $-u$ without exceeding 300 hours per setting.
- The large acceptance of BigBite makes it possible for the data in each setting to be divided into several s-t bins.

Proposed Measurements

Kin	E_{Beam} [GeV]	E_{in} Range [GeV]	s $[\mathrm{GeV}^2]$	-t $[\mathrm{GeV}^2]$	-u $[\mathrm{GeV}^2]$	θ^{cm} [°]	θ_γ [°]	θ_{p} [°]	θ_H^{targ} [°]
L1	8.8	4 - 8	12.1	3.5	6.9	70	21.5	35.5	0
S1	8.8	4 - 8	12.1	3.5	6.9	70	21.5	35.5	-20
L2	11.0	8 - 11	18.7	5.6	11.3	70	17.4	30.5	0
L3	8.8	4 - 8	12.1	5.3	5.2	90	30.2	26.5	0
L4	8.8	4 - 8	12.1	7.0	3.3	110	42.3	19.4	0
S4	8.8	4 - 8	12.1	7.0	3.3	110	42.3	19.4	+80

- Beam-time estimates are based on the requirement of ± 0.1 or better statistical uncertainty in at least one s-t bin.
- The overall systematic uncertainty is estimated to be around 6 - 7 % and is dominated by contributions from the pion background subtraction (shape), the target dilution factor and the proton polarization.
- 200 hours is expected for experimental overheads, such as calibration data-taking, beam polarimetry, target annealing and kinematic changes.

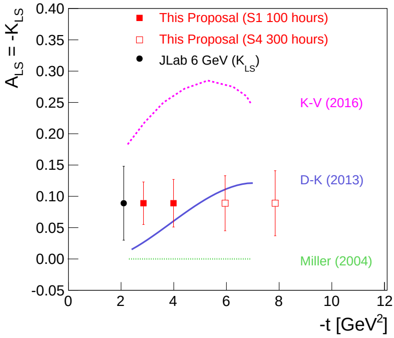


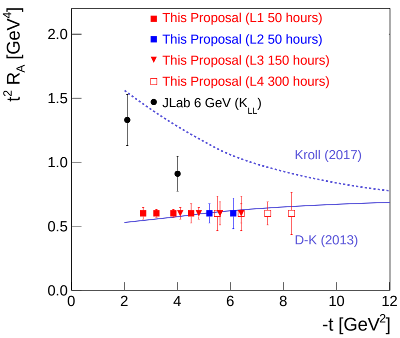


- Make an explicit, model-independent test of factorization by measuring the s-dependence of the polarization observables at fixed θ_p^{cm}, and verify that target mass corrections and higher twist effects are small.

- Measurement of A_{LL} at large CM scattering angle will allow for a singular test of whether current or constituent quarks are the relevant degree of freedom in hard exclusive reactions at these sub-asymptotic energies.

Expected Results – Proton Structure





- Systematically improve our knowledge of the non-perturbative matrix elements of the handbag mechanism in the GPD and SCET approaches.
- Constrain the GPDs $\tilde{H}$ and E at high $-t$ and compare with the Axial and Pauli form factors, which will have a significant and broad impact in the fields of electron and neutrino scattering.

Summary and Beam-time Request

- The WACS programme is unique to Jefferson Lab and offers a relatively unexplored window on hadron structure at high momentum transfer.
- Results from the JLab 6 GeV era demonstrate factorization appears to be valid for Mandelstam variables above 2.5 GeV^2 – this will be tested unambiguously with the proposed measurements.
- The results will have a significant impact beyond WACS and JLab (e.g. at Belle and MINERvA) by systematically improving our knowledge of handbag-based theoretical approaches and transverse proton structure.
- The proposed experimental technique with a high-intensity photon beam and polarized target opens up physics possibilities that have hitherto been inaccessible at tagged photon facilities.

We request 1150 hours of beam-time in Hall C to measure WACS polarization observables with unprecedented precision and kinematic reach.

Kinematic Setting	E_{Beam} [GeV]	s $[\mathrm{GeV}^2]$	-t $[\mathrm{GeV}^2]$	-u $[\mathrm{GeV}^2]$	θ^{cm} $[^\circ]$	Beam-time [hours]
L1	8.8	12.1	3.5	6.9	70	**50**
S1	8.8	12.1	3.5	6.9	70	**100**
L2	11.0	18.7	5.6	11.3	70	**50**
L3	8.8	12.1	5.3	5.2	90	**150**
L4	8.8	12.1	7.0	3.3	110	**300**
S4	8.8	12.1	7.0	3.3	110	**200**
Overhead						200
Total						**1150**

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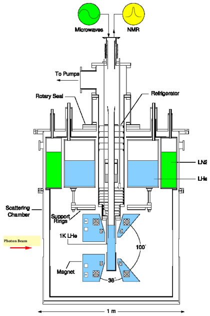
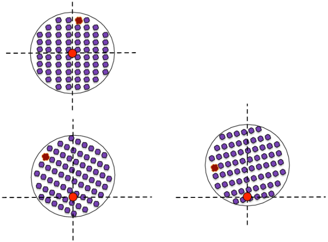
Back-up Slides

- Uniform irradiation of the target cell will be achieved by a synchronized vertical motion of the target ladder and rotation of the target cup.
- In order to do so the NMR coils must be located outside the target cup, which the TAC pointed out was problematic in Hall B.
- We note here that the Hall C target has a much larger volume than in Hall B (14.7 cm^3 vs. 1.8 cm^3) which results in a much cleaner NMR signal.
- Studies at UVa have shown the SNR for proton targets remains unchanged at 7:1.
- We do not believe therefore that the use of the external coils will affect the polarization uncertainty for the proton target.





- "The asymmetries A_{LL} and A_{LS} allow one to separate the different helicity components of the high-t quark GPDs, as well as possible quark helicity-flip contributions to the amplitude due to chiral symmetry breaking."
- The Theory TAC reviewers raise concerns about extrapolation errors on the π^0 cross section, which is expected to scale as $1/s^7$.
- We share their concerns, but note that:
  - Preliminary results from Hall A (E99-114) and CLAS (g12) up to $s = 11\ \mathrm{GeV}^2$ show excellent agreement with s^{-7} scaling.
  - There is much variation in predictions for the WACS cross section – we chose to use the worst-case scenario of $s^{-7.5}$ (D-K13).
- We believe therefore that our rates and dilution projections (as in E12-14-003) are extremely conservative.
- We welcome any theoretical effort on WACS and pion photoproduction and will work closely with them.

J. Sjogren, Glasgow Uni. PhD Thesis (2015)

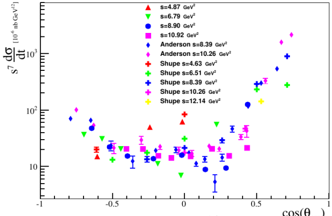


Figure 5.6: pQCD scaled results. $s^7\frac{d\sigma}{dt}$ vs. $\cos(\theta_{cm})$.

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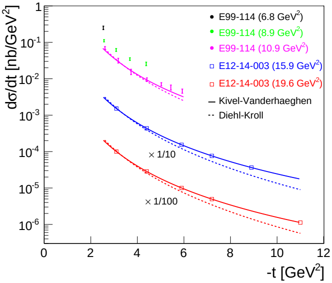

Previous Polarized WACS Proposal E12-14-006

- Approved by PAC42 for 15 days in Hall C.
- With the new experimental technique proposed here, it would be possible to make these measurements with less than 1 day production running.
- The Theory TAC review refers to E12-14-006 as an experiment to measure recoil polarization observables (K_{LL}) – it is not.
- A measurement of recoil polarization for WACS at 12 GeV would be prohibitively beam-time intensive.